FY02 Highlights

- Overview
- Architecture Concepts
- *Exploration Hurdles*
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  - Power
  - Crew Health and Safety
  - Human and Robotic Operations
  - Space Systems
- Technology Planning
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Hurdles: Space Transportation

Current space transportation systems are too costly and inefficient to meet tomorrow's human and robotic exploration requirements.

FY02 Accomplishments Addressing Transportation Hurdle:

- Recommended requirements for the next generations of Earth-to-orbit and nuclear in-space transportation systems
  - Submitted requirements to the Integrated Space Transportation Plan and Space Launch Initiative
  - Identified critical in-space transportation infrastructure to be manufactured in space
- Identified and modeled low energy transfer "interplanetary superhighways" – to increase efficiency
- Developed an integrated nuclear electric propulsion and artificial gravity vehicle system concept – to preserve crew health
- Developed a scaleable, bimodal nuclear thermal/electric propulsion system concept
- Provided seed investments to key transportation technologies (e.g., plasma sails, Hall thrusters, and plasma propulsion) to increase efficiency
- Initiated development of models to assess and optimize spaceport operations – to increase safety and decrease cost

Hurdles: Space Transportation –
Space Launch Initiative Requirements

The U.S. Space Launch Initiative is a central element of NASA's Integrated Space Transportation Plan (ISTP), which is NASA's long range strategy for safer, more reliable, and less expensive access to space.

In November, 2002, NASA released a new, revised Integrated Space Transportation Plan which dedicates more resources to the International Space Station Program; provides additional funding to extend the life and enhance the safety and reliability of the agency's Space Shuttle fleet; boosts funding for science-based payloads and research; and restructures the Space Launch Initiative, originally designed to identify next-generation reusable launch vehicle technology.

The former Integrated Space Transportation Plan consisted of 3 major programs including Shuttle safety upgrades, the 2nd Generation Reusable Launch Vehicle Program, and the 3rd Generation Reusable Launch Vehicle technologies. In partnership with the Department of Defense, the U.S. aerospace industry, and academia, NASA performed systems engineering, technology development and architecture definition trades studies with the goal of defining several 2nd generation reusable launch vehicle architecture designs that would best meet mission requirements.

This document summarizes recommendations developed by NEXT and the International Space Station Program Integration Office with respect to the needs of the 2nd Generation Reusable Launch Vehicle Program.

NASA Exploration Team (NEXT)
Inputs to the 2nd Generation Reusable Launch Vehicle Program
June 11, 2002

Space Launch Initiative Requirements

- A NEXT "tiger team" delivered the report *Inputs to the 2nd Generation Reusable Launch Vehicle Program* to the Space Launch Initiative Program based upon the NEXT Design Reference Missions
- Key NEXT findings include:

Requirements and Process Elements	Importance to NEXT Strategy
Decision Process	Requirements of all stakeholders must be included to assure national leadership in space
International Space Station (ISS) Program	ISS is integral to Stepping Stone paradigm and its requirements must be met by future Earth-to-orbit systems
Extravehicular Activity	No credible alternative to assure assembly, maintenance and service of high value payloads
Assembly and Checkout of OSS Missions	Human/robotic teams most cost-effective for assembly, deployment, activation, checkout, or servicing of future large science platforms
Exploration of the Earth's Neighborhood	Capability needed to launch human vehicle elements and large science platforms for operation beyond low-Earth Orbit
Exploration of Accessible Planetary Surfaces	Earth-to-orbit launch systems must accommodate required minimum mass and volume packaging for human exploration vehicles
Launch of Nuclear Materials	Use of nuclear systems is significantly enabling for deep space human and robotic missions
Manual Override	Necessary for the safety of crew and vehicle

Hurdles: Space Transportation – Workshop for Identification of In-Space Transportation Infrastructure to be Manufactured in Space

Transportation is the indispensable enabler of exploration. Spacecraft propulsion necessitates immediate attention in order to introduce new capability, reduce trip times, drive down costs, and improve safety and reliability. But in order to take economic advantage of these benefits for exploration and development of space, there must eventually be a supporting transportation infrastructure in space. It is attractive, for reasons of economy and function, that much of this infrastructure be manufactured in space.

NEXT conducted a two-and-half day workshop to begin to answer basic questions pertaining to creation of a space transportation infrastructure: What kinds of space activities would a transportation infrastructure enable and serve, and with what functional characteristics? What are the generic elements of a suitable infrastructure? Which of these elements should be or can only be manufactured in space, and with what required manufacturing technologies? And what are the enabling avenues of research and technology development that must be pursued?

The intent for the workshop was not to pre-select transportation architecture and industry "winners" that should be developed, but rather to examine broadly representative architectures and industries previously identified and derive from them the characteristics of the associated transportation infrastructure. The 27 workshop participants identified 17 mission "themes" of future activity in space, sorted them into five possible "modes" of operation (e.g., logistics, observer, station), and identified which of 14 transportation "legs" applied to each. Using that basic analysis as a departure point, this group identified the elements of infrastructure that would be entailed in each theme/mode/leg to provide insight into the associated functional characteristics. This group also identified which elements have systems or subsystems that could or should be manufactured in space (e.g., spares, dunnage, structures and mechanisms) to support the associated mission. The manufacturing technologies required to produce these were reviewed for technical challenges, and research issues to address these challenges were identified.

Workshop Results – Workshop for Identification of In-Space Transportation Infrastructure to be Manufactured in Space, October 25, 2002.
Contact David Harris/MSFC
mailto:david.c.harris@msfc.nasa.gov

Workshop for Identification of In-Space Transportation Infrastructure to be Manufactured in Space

Workshop Objective: To identify critical in-space transportation infrastructure to be manufactured in space and to identify infrastructure elements and the technologies to manufacture them.

Accomplishments/Results:

- Identified 17 mission themes of future activity in space, sorted them into 5 operational modes (e.g., logistics, observer, station), and identified which of 14 transportation "legs" applied to each
- Identified the associated infrastructure elements to provide insight into the associated functional characteristics
- Identified which elements have systems or subsystems that could be manufactured in space (e.g., spares, dunnage, structures and mechanisms)
- Identified materials and processes allowing manufacturing in space, and research issues to surmount

Recommendations:

- Initiate infrastructure working group (architects, researchers, scientists, and manufacturing specialists)
- Develop and analyze inter-dependencies to provide basis for road mapping
- Develop infrastructure (facilities, services, and installations) road maps

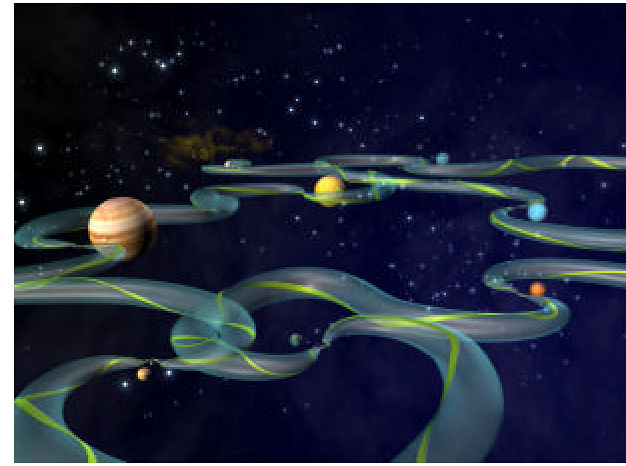
Hurdles: Space Transportation – Interplanetary Superhighway

Conceptually best viewed as tubes, invariant manifolds of unstable orbits were discovered by Poincaré in the 1890's. These low-energy orbits are organized in tubular channels generated by unstable libration orbits and unstable resonant orbits of the Moon and the Earth. Low-energy transport can occur when the tubes intersect, depending on how such intersections occur. In general, lowest energy transport occurs using pathways along these tubes. Most of these low-energy channels still need to be mapped, and the phasing of the tubular intersections requires analysis. New mission concepts using them will undoubtedly emerge as better understanding is developed. In some cases, energy savings are achieved at the expense of trip time. Further analysis is needed to determine the direct utility of the Superhighway for human missions, but it is clear that human missions may indirectly benefit from use of these approaches for cargo transfers.

The key tasks for the development of nonlinear orbital dynamics technology are:

- Mapping the Interplanetary Superhighway (the nonlinear global families of solutions). This requires the development of theoretical tools and algorithms to identify the families of orbits and their connection with other orbits via the trajectory tubes.
- Developing geometric and graphical tools to interact with the geometric structures (high dimensional surfaces called manifolds) in the Interplanetary Superhighway to identify flight paths that meet specific performance characteristics such as propulsion requirements, power and communications geometry, dynamic behavior, etc.
- Integration of dynamic systems theory with optimal control theory to produce a more efficient methodology for generating optimal orbits.
- Development of a multi-scale, multi-domain trajectory design and optimization methodology where conic flybys, nonlinear orbits, and impulsive and continuous thrust trajectories may be designed and optimized in an integrative environment.

Interplanetary Superhighway



(Animation)

FY02 Accomplishments (co-funded by other sponsors):

- **Analysis of the Superhighway Dynamics in the Earth's Neighborhood**
  - Constructed various trajectory options for a lunar sample return mission using libration orbits. All of these orbits are fully integrated with the JPL Ephemeris model
  - Developing an integrated trajectory for a mission to construct a telescope at Earth-Moon L_1, send it to Sun-Earth L_2 and return it to Earth-Moon L_1 for servicing
- **Analysis of Human Mission to Mars L_1 Halo Orbit**
  - Evaluated several round-trip missions from Earth to Mars with a stop in a Sun-Mars L_1 halo orbit. The orbits are fully integrated
- **Analysis of the Interplanetary Superhighway in the Jovian System**
  - Discovered a transfer trajectory from Callisto, flying by Ganymede, finally captured by Europa, that requires less than 25 m/s, but requires 1500 days
- **Interplanetary Superhighway and Low-Thrust Trajectory Optimization**
  - Principal result, based on analysis of a nuclear propulsion continuous-thrust tour of the Jovian moons, is that the invariant manifolds of unstable periodic orbits play a significant role in low-thrust trajectory optimization

Libration Points generate a vast system of low-energy "interplanetary superhighways." This "network" is extremely powerful and useful in many mission scenarios.

Hurdles: Space Transportation – Artificial Gravity Nuclear Electric Propulsion Vehicle System Concepts

Nuclear Electric Propulsion (NEP) performance is characterized by relatively low thrust but high efficiency. This low thrust level should allow thrusting of an artificial gravity vehicle while under rotation due to the resulting small forces and torques, obviating the spindown-burn-spinup sequences required by high thrust systems (however, techniques for continuous thrust vectoring must be established). There may be inherent vehicle configuration synergies between NEP and artificial gravity system concepts. Typically, NEP vehicle designs require long masts or trusses to separate the nuclear power source from the regions of crew habitation. This approach for "radiation shielding" can be very mass-efficient, given light-weight masts. Such structures may also serve as the artificial gravity rotation "arms." Finally, the mass of the power production and conversion systems may serve as a good "counterweight" for the crew habitation systems, allowing a highly synergistic vehicle configuration.

Three electric propulsion technologies were considered in this study: ion thrusters, magnetoplasmadynamic thrusters, and variable specific impulse magnetoplasma rocket (VASIMR) thrusters. For the fidelity of the current analysis, all of these systems have roughly the same performance and thruster efficiencies. The graph shows the characteristics of a 1 MWe electric thruster. For this analysis, 60% jet efficiency was assumed.

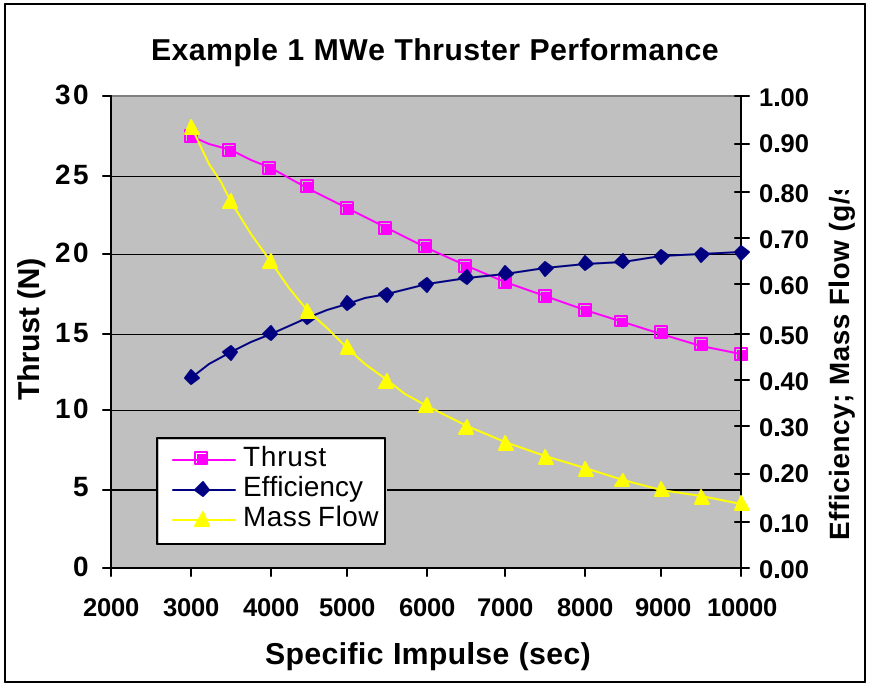
A more important characteristic may be the type of propellant used. Ion and magnetoplasmadynamic thrusters tend to use high-density propellants. This allows efficient propellant tankage and packaging near the vehicle spin axis. The propellant tanks in the figure are sized for magnetoplasmadynamic thrusters (lithium, 500 kg/m^3) and would be smaller for ion thrusters (argon, 1,400 kg/m^3). The propellant of choice for VASIMR, however, is hydrogen, which would have severe configuration impacts for an artificial gravity vehicle. It may be possible to fuel a VASIMR thruster with denser fluids, such as deuterium or nitrogen, and alleviate some of these issues.

Artificial Gravity Nuclear Electric Propulsion Vehicle System Concepts

- Nuclear Electric Propulsion is a good match with artificial gravity for vehicle design
  - Technology horizon ~ 2015
  - Specifications
    - Isp: 4,000 – 6,000 sec
    - Power: 5 – 12 MWe
    - Specific Power: 4 – 8 kg/kWe
  - Reusability: at least 3 missions
    - Consistent with high energy density potential of nuclear systems

(Animation)

- Electric Propulsion Options – Ion, magnetoplasmadynamic, and Variable Specific Impulse Magnetoplasma Rocket (VASIMR) thruster technologies appear most promising for scalability to high power
  - Ion Thrusters
    - Pros: Operational at low power, propellant properties
    - Cons: Grid scaling
  - VASIMR
    - Pros: Lifetime, scaling
    - Cons: Low maturity, propellant properties
  - Magnetoplasmadynamic Thrusters
    - Pros: Tested at 100's kWe, compact
    - Cons: Lifetime



Hurdles: Space Transportation – Scaleable, Bimodal Nuclear Thermal/Electric Propulsion System Concept for Mars Cargo and Piloted Missions

NEXT has developed a bimodal nuclear thermal/electric propulsion system concept for Mars missions which:

- Provides high I_{sp}, high thrust, and propulsive planetary capture
- Provides low thrust with bimodal power production for electric propulsion thrusters

This system is an energy rich source supporting:

- High data rate communications with Earth
- Active refrigeration for long term liquid hydrogen storage
- Life-support and environmental systems for human missions

The piloted vehicle configuration rotates and is capable of providing artificial gravity equivalent to Martian gravity on the outbound leg and equivalent to Earth gravity on the return trip.

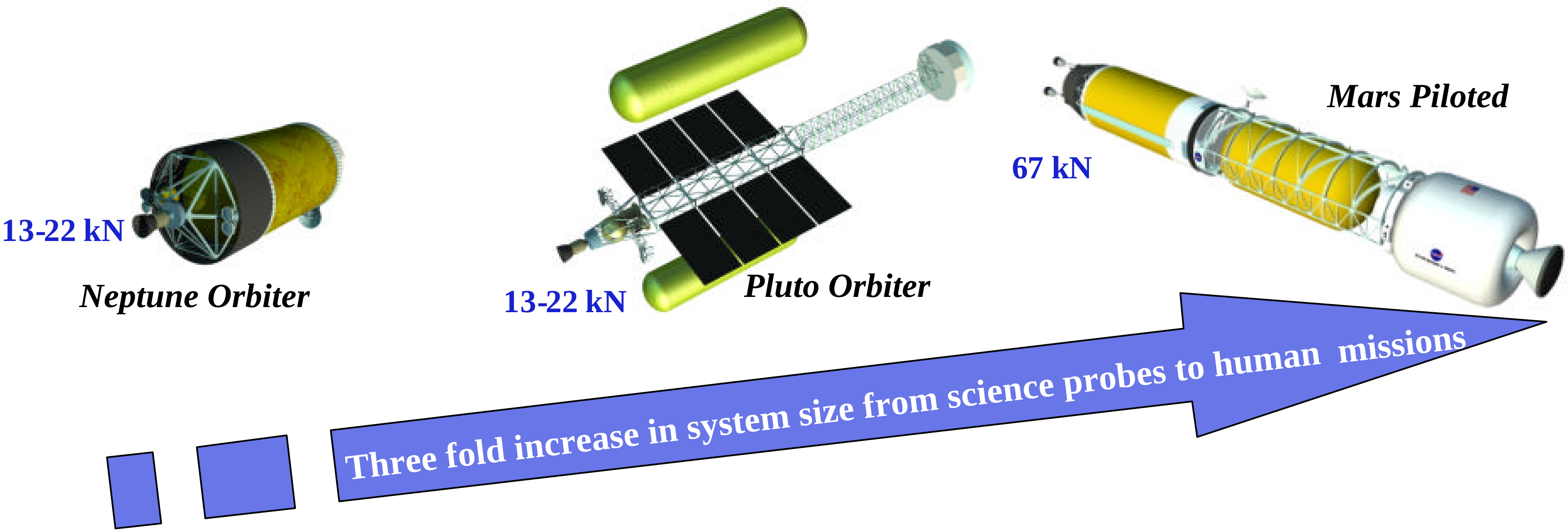
A significant advantage of the bimodal nuclear thermal/electric propulsion is the modest 3-fold scale-up factor from science probes to human-class missions. This is in contrast with nuclear electric propulsion systems requiring a 50-100 factor increase in size from uncrewed science missions to human piloted vehicles.

Studies have identified options for contained exhaust testing for bimodal rockets engines up to 67 kN thrust at Department of Energy facilities.

The joint NASA – Atomic Energy Commission Nuclear Engines for Rocket Vehicle Applications (NERVA) program in the 1960's demonstrated this technology by testing 20 rocket engines up to 1,110 kN thrust. The current size envisioned is an order of magnitude less than what was previously tested for a human class mission.

Hurdles: Space Transportation

Scaleable, Bimodal Nuclear Thermal/Electric Propulsion System Concept for Mars Cargo and Piloted Missions



- "Bimodal" piloted Mars stage produces 200 kN thrust and 50 kW_e
  - 13-67 kN engines, T/W_{eng} ~3.1; 3-25 kWe Brayton power conversion (same size Brayton for all missions)
  - Life support, active refrigeration, housekeeping and electric propulsion option
- Modest system scaling to human class missions
- Innovative "saddle" truss design allows easy tank jettisoning
- Vehicle rotation (w = 4-6 rpm) can provide Mars gravity outbound and Earth gravity inbound (available option)
- Propulsive Mars capture and departure on piloted mission
- Fewest mission elements, simple space operations and reduced cre w risk
- Probe mission develops technologies for human missions with mode st scale-up

Hurdles: Space Transportation – Transportation Technology Seed Investments

NEXT investments in space transportation technologies address cost, safety, and efficiency (i.e., speed, specific impulse, and propellant requirements) metrics. Continued development of these technologies offer the potential to enable multiple classes of human and robotic missions throughout the solar system.

Plasma Sails

Plasma sails (mini-magnetospheric plasma propulsion or M2P2) use solar wind plasma for propulsion. This type of propulsion also has the possible advantage of providing radiation protection for the crew. Laboratory testing of a prototype has shown that it is an exceptionally efficient plasma source.

Plasma Propulsion

Plasma propulsion concepts, such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine, may provide a new method of propulsion that can substantially reduce interplanetary flight time. Current laboratory activities are focused on plasma production, diagnostic techniques, and development of an International Space Station flight experiment.

50 kW Hall Thruster

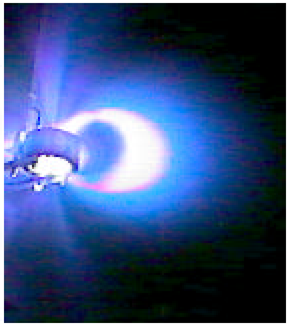
The Hall thruster is an electric rocket engine which generates thrust via an electrostatic acceleration of ions in crossed electric and magnetic fields. This type of engine has potential applications in Earth orbital as well as interplanetary missions. Activities have focused on improving engine efficiency including specific impulse and lifetime.

Advanced Entry, Descent, and Landing System Technologies

Technology advances will provide a variety of materials and systems which can be tailored to specific applications including Earth return and planetary atmosphere entry (e.g., Mars, Venus, Neptune/Titan).

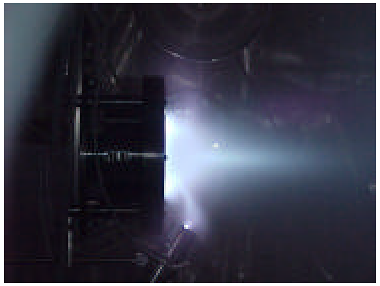
Transportation Technology Seed Investments

Plasma Sails



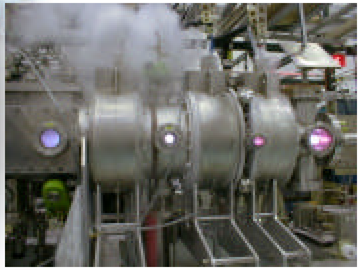
- Propellantless, rapid space transportation with inherent radiation shielding
- Efficiency measurement planned by the end of calendar year 2002

50 kW Hall Thruster



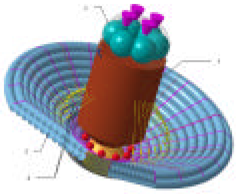
- Highly efficient/higher thrust for solar electric propulsion
- 72 kW operation demonstrated
- Initial tests with xenon propellant has proven viability of design

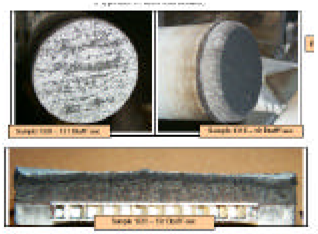
Plasma Propulsion



- High power, variable specific impulse thruster
- Ongoing thruster development
- Independent review planned for October 2002

Advanced Entry, Descent, and Landing System Technologies





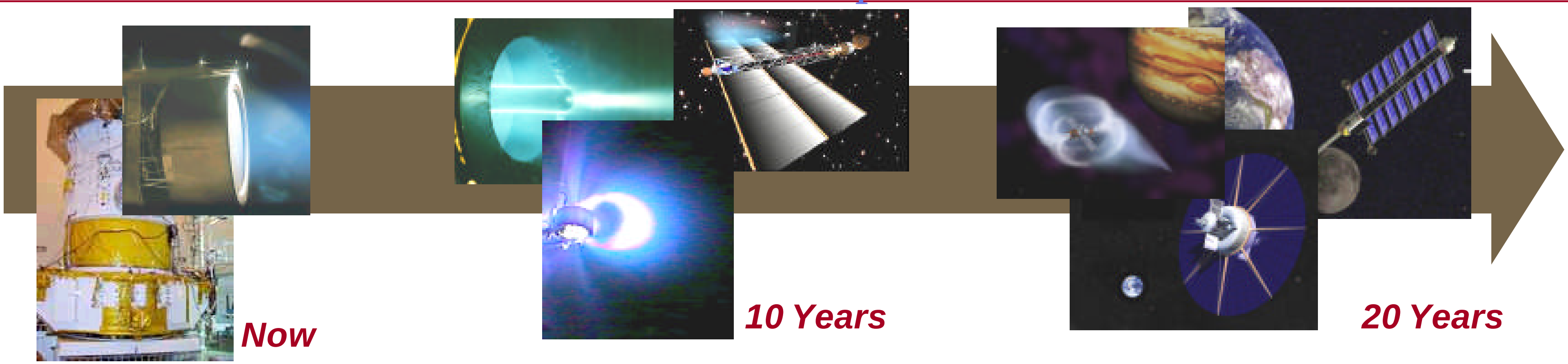
- Entry, descent, and landing efforts to expand supersonic decelerator capability in planetary atmospheres
- Charring ablator advances including cost and weight savings and increased diversity
- Strip-collar bonding manufacturing of heat shields

Hurdles: Space Transportation – Many Technologies Extend to a Broad Range of Future Human/Robotic Exploration Missions

Selected nuclear system technologies, currently under consideration, may possess the ability to overcome space transportation hurdles and enable future ambitious, affordable, and safe missions of human/robotic space exploration and development. In considering future technologic paths, one criteria for decisions is whether the system technologies and/or major system components are evolvable to future human/robotic missions. For the successful evolution of technologies, fabrication, and ground-based capacities envisioned for the first nuclear propulsion mission to human/robotic missions, these systems and/or components must be scalable to applications requiring on the order of megawatts. The scalability of these nuclear system technologies is one of many criteria that must be addressed for technology investment decisions.

Hurdles: Space Transportation

Many Technologies Extend to a Broad Range of Future Human/Robotic Exploration Missions



- **Many of the technology, fabrication, and ground-based capacities developed for the first space nuclear propulsion mission have direct application to follow-on missions**
  - Nuclear fuel and clad and fabrication capacity
  - Nuclear reactor design, analysis, qualification methodology and software
  - Neutron and gamma shielding; neutron reflector; fabrication capacity
  - Radiation-tolerant nuclear reactor instrumentation and control; fabrication capacity
  - Space nuclear reactor power system autonomy
  - Power conversion and fabrication capacity
  - Low mass, large-scale radiation-tolerant thermal radiators and fabrication capacity
  - High power density electrical power control and distribution; fabrication capacity
  - High power electric propulsion and fabrication capacity
  - Safety and launch approval procedures, National Environmental Policy Act procedures and actions
  - Ground test facility and support equipment (both for zero-power critical testing, and potential full power testing)

Nuclear propulsion technologies are evolvable for follow-on, science-driven human/robotic exploration missions.

Hurdles: Space Transportation – Modeling and Optimization of Spaceport Operations and Logistics

Risk is inherent to space exploration. When there is human presence in exploration, capabilities multiply, but so do the possibilities for error. One essential element in addressing both risk and cost management of human-in-the-loop processes, especially those conducted far from Earth where ground-based resources are unavailable, is greater automation of hazard identification and control including application of artificial intelligence.

The Spaceport Safety Modeling and Optimization task advances the state-of-the-art of a key risk management tool, Human Factors Process Failure Modes & Effects Analysis, that is presently very labor intensive. This advanced implementation of Human Factors Process Failure Modes & Effects Analysis is flexible enough to analyze exploration, spaceport, and maintenance operations. Any extended missions, including those to the Moon, Mars, or an asteroid, will require the crew to perform various maintenance activities. This tool could be used to collect and analyze data on maintenance processing scenarios from a crew perspective to enhance and assure crew performance and well-being. The tool depicts how safety issues and hazards are linked to cost of operations and how processes can be designed to mitigate safety and health risks as well as reduce costs.

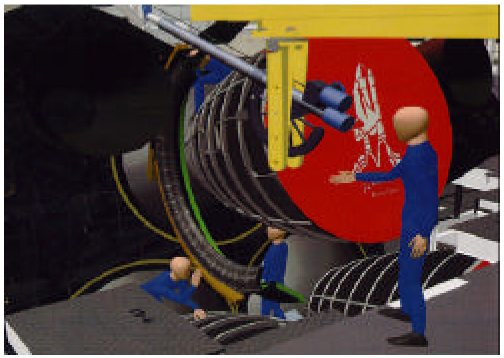
A key factor in the design and development of exploration spacecraft is provision of spares. Component choices and their expected reliability must be taken into account in planning maintenance and system outage procedures, and in system design to support those procedures. The earlier in design that these variables can be accurately estimated, the earlier the design case can close.

Modeling and Optimization of Spaceport Operations and Logistics

Progress is being made to assess and influence vehicle / mission architectures to be more "operations friendly"

- Reduced cost
- Increased safety / reduced risk
- Increased efficiency

Spaceport Safety Modeling & Optimization



Importance

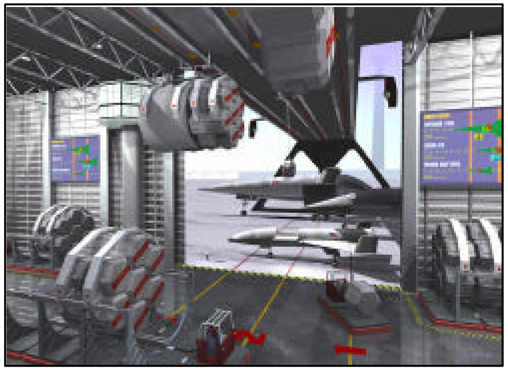
– Provides a rapid task analysis capability to identify performance shaping factors and generates recommendations to mitigate or reduce human errors

– Depicts how safety issues and hazards are linked to costs of operations

Accomplishments

– Prototype model to assist performing a human factors process failure modes & effects analysis is complete

Logistics Assessment for System Upgrades



Importance

– Identifies on-board spares requirements based on key mission parameters (crew size, mission duration, required system reliability and crew maintenance time)

– Allows mission planners to assess spares mass/volume impacts to system architectures

Accomplishments

– Prototype model, user's guide, analyst's guide, and methodology document delivered

– Model to be implemented in assessing trade analysis

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